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Improving the performance of DTP2 bilateral teleoperation control system with haptic augmentation

Mikko Viinikainen*, Janne Tuominen, Pekka Alho, Jouni Mattila

Department of Intelligent Hydraulics and Automation, Tampere University of Technology, Finland

HIGHLIGHTS

- An experimental haptic shared control system, called CAT developed at the DTP2.
- We investigate how the system integrates with the ITER compliant DTP2 RHCS.
- The effect of CAT experimentally assessed in an ITER relevant maintenance scenario.

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ABSTRACT

The remote maintenance of the ITER divertor is largely dependent on the usage of haptically teleoperated manipulators and man-in-the-loop operations. These maintenance operations are very demanding for the manipulator operators, yet vital for the success of the whole ITER experiment. Haptic shared control of the maintenance manipulators offers a promising solution for assisting the teleoperators in the maintenance tasks. A shared control system assists the operator by generating artificial guiding force effects and overlaying them on top of the haptic feedback from the teleoperation environment.

An experimental haptic shared control system, called the Computer Assisted Teleoperation (CAT) has been developed at the Divertor Test Platform 2 (DTP2). In this paper, we investigate the design of the system and how the system integrates with the ITER compliant DTP2 prototype Remote Handling Control System (RHCS). We also experimentally assess the effect of the guidance to the operator performance in an ITER-relevant maintenance scenario using the Water Hydraulic MANipulator (WHMAN), which is specially designed for the divertor maintenance. The result of the experiment gives suggestive indication that the CAT system improves the performance of the operators of the system.

1. Introduction

Haptic bilateral teleoperation is a challenging and mentally demanding job for the operators of robot control systems. It is especially difficult in cases such as the remote maintenance of the ITER divertor region. Particularly, the weights of the handled divertor components and required accuracies are high, and the space around the components is constricted [1]. Most of the divertor maintenance tasks require bilateral teleoperation (man-in-the-loop) due to the complex tasks and limited viewing system [2].

Virtual reality and operator support systems can be used to reduce the amount of mental and physical workload perceived by the operators and make teleoperation tasks faster and safer. Especially haptic shared control systems have been demonstrated to improve teleoperation results significantly (e.g. [3–5]). The concept of this kind of system, first proposed by Rosenberg [3], is to assist the operators during haptic bilateral teleoperation tasks by generating virtual forces based on virtual models of the teleoperation environment and sensor data from the slave manipulator. These artificial assisting forces are combined with force feedback signals from the teleoperation environment. The assisting forces make bilateral teleoperation more efficient and safer by guiding the operator to the point of interest in the teleoperation environment, and by damping motion when close to contact with protected areas of the teleoperation environment. A system called Computer Assisted Teleoperation (CAT) has been implemented at the Divertor Test Platform 2 (DTP2) to provide shared control mode for the operators.

The purpose of this paper is to investigate the effectiveness of the implemented CAT techniques in the DTP2 setup within an ITER representative Remote Handling Control System (RHCS). The effect of the guidance provided by CAT is evaluated in an ITER relevant divertor maintenance experiment. The slave device in

* Corresponding author. Tel.: +358 401981221.
E-mail address: mikko.viinikainen@tut.fi (M. Viinikainen).

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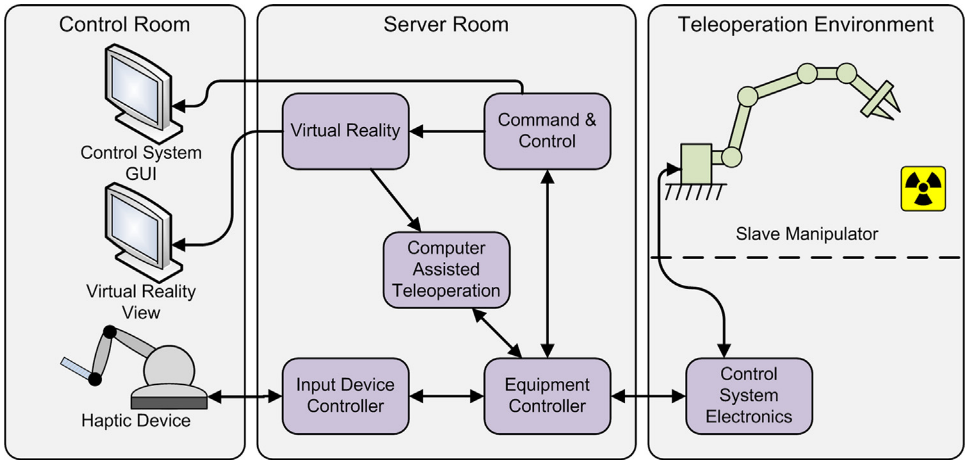

Fig. 1. Architectural view of subsystems contributing to the bilateral control of the WHMAN.

the experiment is the Water Hydraulic MANipulator (WHMAN), which has been developed for the divertor cassette replacement and ITER environmental conditions. During the experiment, the execution times of the teleoperation task and operator workload were observed to assess the performance of the CAT system.

Section 2 of this paper introduces the DTP2 RHCS and the manipulators, used in the shared control experiment. Section 3 introduces the CAT system and its integration to the DTP2 RHCS. Section 4 describes the shared control experiment and Section 5 the results of it. Section 6 is the discussion of results and Section 7 presents the conclusions.

2. Background

2.1. DTP2 Remote Handling Control System

The DTP2 RHCS architecture is an adaptation of the ITER RHCS architecture [6]. The parts of the control system that are related to the bilateral control of the manipulators are:

- Command & Control (C&C),
- Equipment Controller (EC),
- Input Device Controller (IDC),
- Input Device (ID),
- Computer Assisted Teleoperation (CAT),
- Virtual Reality (VR).

All of these subsystems, except the input device, are developed in-house for the DTP2 research. Relations between the subsystems are presented in Fig. 1.

The control system, introduced in Ref. [7], implements a master-slave bilateral teleoperation scheme, where a commercial haptic device (Phantom Premium 3.0 6 DOF) is used as the master and the WHMAN as the slave manipulator. The C&C subsystem provides operators with a graphical user interface for the devices. The VR subsystem provides a virtual representation of the teleoperation environment and is used for setting up the virtual models to the CAT system. The assisting virtual forces are reflected to the master side of the bilateral teleoperation system.

2.2. Slave manipulator

The slave manipulator used in this experiment is the WHMAN, introduced in Ref. [8]. This manipulator has been developed specifically for the environmental condition of the ITER divertor and maintenance tasks that require high agility (Fig. 2).

Fig. 2. 6 DOF Water Hydraulic MANipulator (WHMAN).

The WHMAN is composed of a robotic arm (with three rotational joints and one prismatic joint) and a spherical wrist (three rotational joints) that is attached to the end of the arm. The whole manipulator is installed on top of a linear joint. All the joints are used continuously and concurrently so that the manipulator achieves redundancy with eight active joints. A 6 Degree of Freedom (DOF) force sensor is attached to the tip of the manipulator. This allows contact force and torque measurements that are used for the haptic feedback.

2.3. Master device

The master device used with the DTP2 RHCS is a Phantom Premium 3.0 6-DOF-haptic device, manufactured by Geomagic-Sensable. The device provides force feedback in three translational degrees of freedom and torque feedback in three rotational degrees of freedom.

The work space of the haptic device is much smaller (approximately 900 mm × 900 mm × 300 mm) than the work space of the slave device (approximately 5000 mm × 4500 mm × 4500 mm) [8,9]. The movements between these manipulators are also scaled (5:1 ratio used in this experiment). To allow the usage of the manipulators with such different scales a push button is available on the haptic device handle for re-indexing. When the button is not pressed, the master manipulator is disengaged from the slave and can be repositioned independently. Pressing and holding the push button engages the master with the slave and the operator can start controlling the motion. The device also electrically recognizes the presence of the operator's hand and disables force feedback if the hand is not present.

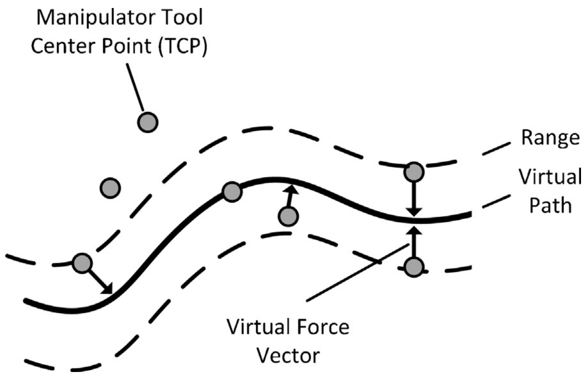

Fig. 3. 2D presentation of a virtual path. The generated virtual force vector is proportional to the distance between the manipulator TCP and the path.

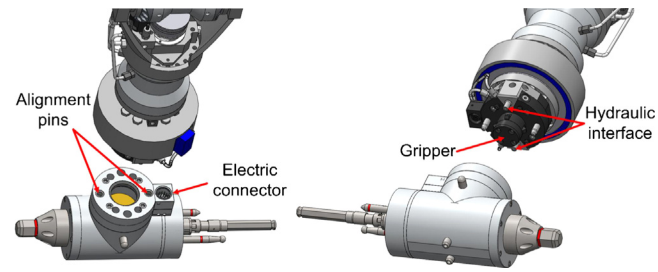

Fig. 4. WHMAN tool changer interface and the wrench-pin tool.

3. DTP2 shared control

3.1. Computer Assisted Teleoperation

The CAT subsystem is the part of the DTP2 RHCS that is dedicated for assisting operators of the Remote Handling (RH) devices in bilateral teleoperation tasks. CAT implements two different kinds of assistance functions. These are point cloud based guiding virtual paths and oriented bounding box based resisting virtual walls. Only virtual paths were used in this experiment.

As can be seen in Fig. 1, CAT is connected to the VR and EC. The communication from the VR to CAT is unidirectional and uses the control network of the DTP2 RHCS. Through this communication link CAT receives the information about virtual models of the RH-environment. Communication with the EC is bidirectional and has real-time constraints. Through the EC communication link CAT receives information about the manipulator position and sends the virtual force information to the low level controllers. All interfaces of the CAT system are implemented using the Data Distribution Service (DDS) middleware.

In this experiment, the CAT subsystem was executed on a dedicated industrial PC. The CPU of the computer is a single core Pentium 4 with 2.4 GHz clock speed. The operating system of the PC is Debian Linux with Xenomai real-time kernel extension that the CAT software takes advantage of.

3.2. Virtual paths

Virtual paths are implemented in CAT by connecting the points of a point cloud with straight lines from one point to another. The path starts generating virtual forces when the Tool Center Point (TCP) position of the manipulator is in the range of the path. CAT only generates forces that are perpendicular to the path. Therefore, operators are free to move back and forward along the path. Path guidance can be turned off by moving the manipulator TCP outside the range of the path or by turning the path off. Fig. 3 is an illustration of a 2D virtual path.

Virtual paths of CAT are of the impedance [10] type. The force generation algorithm of virtual paths is run at a 1 kHz frequency. At each iteration, the algorithm goes through every point cloud that is stored in to the working memory of CAT and generates the virtual force effect. Virtual paths of the DTP2 CAT do not take the orientation of the manipulator into account.

4. Experiment description

4.1. Task description

The ITER divertor cassette locking sequence [11,12] was analyzed to determine a suitable teleoperation task for the haptic shared control experiment. The task chosen is a frequent occurring procedure to attach a tool to the WHMAN. Attaching to the various tools used in the cassette locking sequence with the WHMAN requires high accuracy and adaptability due to the mechanical interface of the WHMAN tool changer. Automation of the tasks is hardly possible. Fig. 4 shows the interfaces of the WHMAN tool changer and the wrench-pin tool, which was used in the experiment.

When attaching to the wrench-pin tool, the WHMAN approaches the tool changer interface from above. The operator adjusts the orientation and location of the WHMAN with the master device to align the alignment pins and the electrical connector of the WHMAN. When the pins and the connector are aligned the operator inserts these inside the wrench-pin tool.

4.2. System configuration

The WHMAN, together with the full DTP2 RHCS, was used in the shared control experiment. The experiment was performed on a mock-up test stand, which is geometrically identical to the divertor cassette locking system.

The haptic guidance tested in the experiment consisted of two virtual paths that guided the operators to the tool changer interface. The paths were parallel with the sockets of the tool changer alignment pins and laid over each other. The purpose of the path setup was to provide one path with a long range but a small force effect to give a rough guidance to the interface. Another path had a shorter range and a stronger force effect for guiding the precise alignment of the alignment pins. Both paths were straight lines. Fig. 5 shows the paths, the manipulator tool changer and the tool interface.

The range of the path for rough guidance was 50 mm and stiffness 150 N/m. Respectively, the range of the path for precise alignment was 15 mm with 500 N/m stiffness.

Participants had direct vision of the slave manipulator during the experiment. However, the operators were not able to see the tip of the manipulator or task-related details directly and were specifically instructed to rely on the visualization model and a video feed from the environment. A snapshot from the virtual model and the low resolution video feedback available for the operators during the experiment are shown in Fig. 6.

4.3. Experimental procedure

During the experiment, 10 participants were asked to perform the attach operation twice with the WHMAN. One of the operations was done with the CAT system enabled and another without the

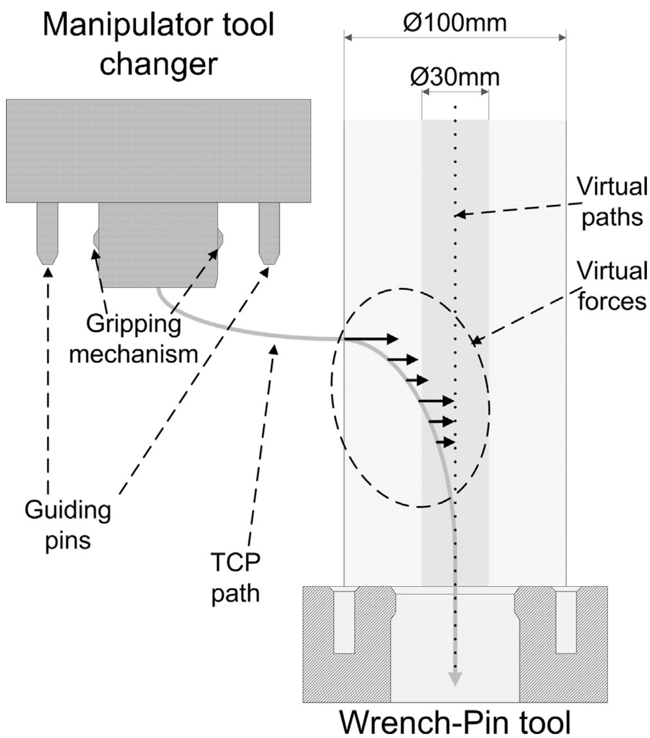

Fig. 5. The attachment task overview.

assistance from CAT. None of the operators had extensive previous experience about haptic bilateral teleoperation but all operators were familiar with the concept. Before the experiment the task and the Task Load Index (TLX) method, used for assessing the perceived workload, was explained to the operators. Each operator was given approximately five minutes training time with the teleoperation system before the test. Altogether, the test took about 30 min for each operator.

Each of the attachment tasks started from the same position in the workspace. The start position was outside of the effective range of both virtual paths, forcing the operators to rely also on visual clues, and not just to the haptic guidance. The task was concluded when the manipulator was fully inserted to the tool. Participants conducted the two parts of the experiment in succession. To reduce the systematic error caused by learning, a counterbalanced test method was used. Therefore, half of the operators performed the test first with the CAT system enabled and the other half with the CAT system turned off.

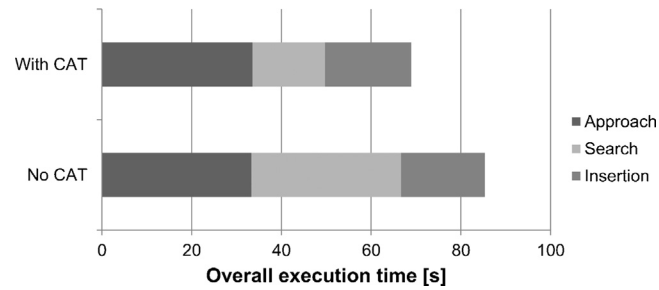

Fig. 7. Task execution times, divided into parts according to recorded slave manipulator trajectories.

4.4. Data analysis and metric

The RHCS was used for data logging during the experiment. Particularly, the trajectories of the manipulators and contact forces were logged at a 50 Hz frequency. After each tool attachment operation, participants filled a TLX questionnaire form. The TLX method, developed by NASA, is a rating procedure that rates the perceived workload that the test subject experiences and divides the overall score to six subscales [13].

5. Results

The recorded trajectories of the tool attachment tasks were divided into three subsections for analysis. These were the approach, interface search and insertion phases. The approach phase constitutes the time from the initial location to the first physical contact between the wrench-pin tool and the manipulator tool changer. Interface search time was counted from the first physical contact to the point where the tool changer alignment pins were slightly inside their sockets for the first time. The insertion phase is the time taken from the slight insertion of the alignment pins to the perfect insertion.

The spread of the execution times between the participants was large. The standard deviation for the unguided operations was 55.9 s and for guided operations 23.4 s. The data also showed strong evidence that subjects improved their performance by learning during the task execution. This resulted on average in a shorter task completion time in the second condition. In this paper the statistical significance of collected data is evaluated using paired t-tests. The limit of statistical significance is consider to be $p = 0.05$. Recorded mean execution times are presented in Fig. 7.

The overall execution time of the task show a difference in means of 18.4 s ($p = 0.17$). However, as indicated by the p-value, this result cannot be considered statistically significant. The approach and insertion phases of recorded tasks were performed in

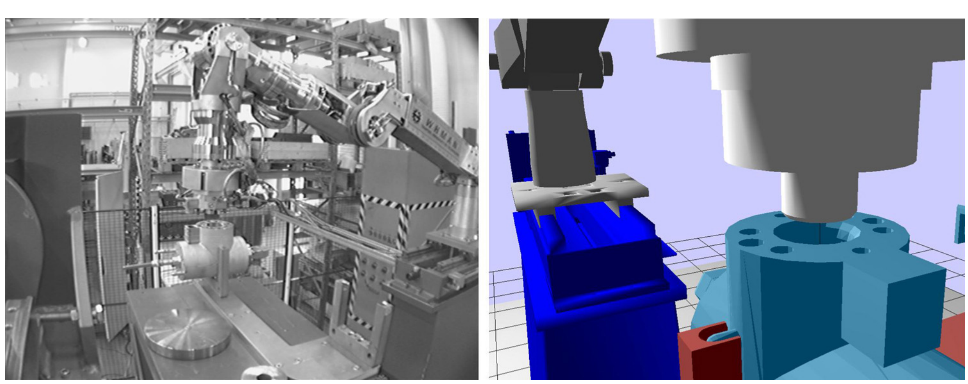

Fig. 6. Views of the teleoperation environment available for operators during the experiment.

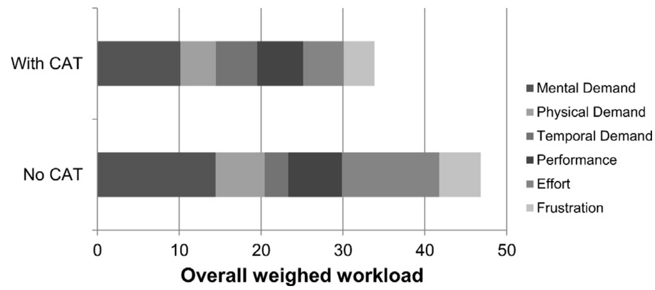

Fig. 8. Results of the TLX tests.

approximately the same mean time, both with CAT and without it. The difference between the mean times of the search phase was 17.2 s ($p = 0.07$).

All but one of the operators experienced a drop in the workload level. The TLX test revealed that the overall mean perceived task load was 27.5% ($p = 0.089$) lower on average when CAT was used. Detailed analysis results are presented in Fig. 8.

The mental demand was on average the largest contributing factor in the workload for both test cases. Difference between the mean mental demand results between test cases was 29.8% ($p = 0.057$). Another large factor was the effort measure which was 58.3% ($p = 0.008$) lower when operating with CAT.

6. Discussion of results

The task completion time is not significantly reduced by CAT. Significance of the results might be increased when more operators are tested or more repetitions are performed per condition (with/without CAT). In that case the current results are already suggestive that task completion time reduces by CAT, which matches with similar previous experiments (e.g. [3–5]). However, differences in mean execution times were observed mainly in the interface search phase, unlike in many previous researches, where the guidance improves the whole task execution. Perceived mean workloads were also lower in five of the six subscales of the TLX analysis, when teleoperating with the CAT system.

The measured difference of mean task execution times, particularly in the search phase, was encouraging. It should also be noted that the system is the first prototype version of the system and the application still has a lot of room for improvements. The results presented in this paper are suggestive since the amount of experimental data is not sufficient to prove statistically the effect of the system. To get more conclusive results, more experiments need to be conducted.

It came apparent during the tests that operators have very different approaches to the task in hand when they are not precisely asked to perform the task in a specific manner. Also learning seems to affect the time the task takes. Response to assisting forces is also rather individual. One of the test subjects found the assisting force disturbing and performed clearly better without the assistance. Due to the fact that the operators react differently to the haptic assistance, better results could possibly be gained with a system that takes into account the personal preferences of operators.

7. Conclusion

The experiment described in this paper gives a suggestive indication that the CAT system improves the performance of operators in an ITER divertor maintenance relevant teleoperation task. However to statistically prove this claim larger amount of data needs to be generated.

The remote maintenance tasks of ITER are demanding operations that are performed in multiple shifts and are tightly scheduled. Therefore, even small improvements in the task execution times, operator workload or operational safety can generate large improvements to the overall flow of maintenance operations. Therefore, well-tuned and reliable haptic shared control systems are important in the scope of the whole ITER maintenance. The CAT haptic shared control system of the DTP2 RHCS has been successfully used in the divertor remote maintenance operations research at the DTP2 and is sufficient in this scope. However, further research is required to unleash the full potential of the shared control in the full ITER maintenance scope.

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